UNIVERSITI PUTRA MALAYSIA

A HYDROLOGIC MODEL FOR STUDYING THE CLIMATE CHANGE IMPACT ON EVAPOTRANSPIRATION AND WATER YIELD IN A HUMID TROPICAL WATERSHED

AMJAD NABI

A HYDROLOGIC MODEL FOR STUDYING THE CLIMATE CHANGE IMPACT ON EVAPOTRANSPIRATION AND WATER YIELD IN A HUMID TROPICAL WATERSHED

By

AMJAD NABI

Dissertation Submitted in Fulfilment of the Requirements for the Degree of Doctor of Philosophy in the Faculty of Engineering
Universiti Putra Malaysia

January 1998

Dedicated to my beloved sister late Dr. BUSHRA

ACKNOWLEDGEMENTS

With a deep sense of gratitude the author would like to acknowledge his supervisor, Associate Professor Ir. Dr. Mohd. Amin Mohd. Soom for his direction, advice, encouragement and personal interest during the period of this study. Sincere thanks are extended to the members of the committee, Assoc. Prof. Dr. Salim Said, Dr. Shattri Mansor and Assoc. Prof. Kwok Chee Yan for their support, cooperation and guidance. Special thanks are for Prof. Dr. Mohd. Arif Hussein, Dean of the Graduate School and his staff for making arrangements to finalize the study.

The author has no words to thank Dr. Mohd Amin for awarding financial support in the form of Research Assistantship at the Faculty of Engineering, UPM without which this study for the degree of Ph.D would not have been possible. Special thanks are also extended to Dr. Abdul Aziz Zakaria, Dr. Shattri Mansor and Dr. Salim Said for awarding research assistantship in the early stages of this study.

The author is highly grateful to the staff of the Photogrammetry laboratory of the Faculty of Forestry, UPM for their cooperation in the use of their remote sensing and GIS facilities. The author is thankful to technical staff Mr. Abdul Habir Alias and Mr. Mohd. Yusof Yaacob for their cooperation and hospitality during the laboratory work. Special thanks to Assoc. Prof. Dr. Idress Ahmad, Department of Mathematics for his useful suggestions and advice during the analysis stage of this study. The author would also like to thank technical staff Mr. Mahbub Shah, Faculty of Agriculture for assisting in field data collection at Trolak site. Cooperation of all Faculty staff members especially Mr. Meh and Mr. Ghazali is also acknowledged.

The author wishes to thank Dr. Lim Jit Sai of the Department of Agriculture Malaysia for providing the unpublished detailed soil data of study area. The author would also like to thank Mr. Azmi and staff of the Hydrology Branch of Drainage and Irrigation Department, and the staff of the Meteorology Department of Malaysia, for providing the hydrometeorological data used in the study. The author would also like to thank the staff of the Malaysian Centre for Remote Sensing (MACRES), for the providing the satellite data used in the study.

The author wishes to thank his friend Dr. Fayyaz Ashraf and Mr. Ibrahim Khalil (former UPM students) for their encouragements during the course of study. The author is also thankful to his fellows for their cooperation, friendship and good time at UPM.

Finally, the author wishes to express his profound gratitude and appreciation to his wife, Khadija, son, Ahmad Nabi and beloved parents, sister and brothers who always prayed for his success.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATION

α	surface albedo
γ	psychrometric constant
Δ	slope of saturation vapour pressure curve at air temperature
δe	vapour pressure deficit from canopy to air
λ	latent heat of vaporization
ρ	density of air
AET	actual evapotranspiration
BLAI	base leaf area index
C	canopy storage depth
CC	canopy conductance
CCM	Global Community Climate Model
C_{max}	canopy maximum storage depth
CNRD	canopy average radiation per unit leaf area index
CNTA	contributing area for surface runoff as proportion of each GRU
c_p	specific heat of air
C_x	current depth of intercepted rainfall
D	soil moisture drainage
DARD	daily potential solar radiation for the slope and aspect of the GRU
DAYL	day length
E	daily evaporation depth
ELECR	mean elevation correction factor
ERDAS	Earth Resources Data analysis System
EROS	Earth Resources Observation System
ET	evapotranspiration
EXT	light extinction coefficient
F	daily infiltration
$g(\delta\theta)$	function for soil moisture deficit
$g(\delta q)$	function for atmospheric specific humidity deficit
g(L)	function for leaf area index
$g(S_T)$	function for solar radiation
g(T)	function for temperature
GCMs	Global Circulation Models
GFDL	Geophysical Fluid Dynamic Laboratory
GIS	Geographic Information System
GISS	Goddard Institute for Space Studies
g_{max}	maximum canopy conductance
GPST	beginning day of active growing period

GR	groundwater recharge
GRUs	ground response units
gs	stomatal conductance
GS	groundwater storage
HORD	daily potential solar radiation for a horizontal surfaces
HTVCHM	Humid Tropical Vegetation Climate Hydrologic Model
IPCC	Intergovernmental Panel on Climate Change
ISODATA	Iterative self-organizing data analysis techniques
JICA	Japan International Cooperation Agency
JLDY	Julain day
K_1	linear routing coefficient for each subsurface reservoir.
K_2	nonlinear routing coefficient for each subsurface reservoir.
K_b	routing coefficient for groundwater reservoir
K_q	humidity coefficient for canopy conductance
K_R	daily recharge rate from subsurface reservoir to groundwater reservoir.
K_s	radiation coefficient for canopy conductance
K_T	temperature coefficient for canopy conductance
K_{VI}	an attenuation
LAFC	leaf area index adjusting factor
LAI	leaf area index
M	available soil moisture
M_a	current available soil moisture in the soil profile
MACRES	Malaysian Centre of Remote Sensing
M_c	maximum soil water holding capacity of soil profile
MCA	minimum possible contributing area for surface runoff
M_{cL}	maximum available soil moisture capacity of discharge zone
M_{cu}	maximum available soil moisture capacity of recharge zone
M_I	soil moisture index
M_L	current available soil moisture in discharge zone
M_u	current available soil moisture in recharge zone
MXA	maximum possible contributing area for surface runoff
NCAR	National Centre for Atmospheric Research
NDVI	normalized difference vegetation index
NIR	near-infrared reflectance
OBRD	daily observed solar radiation
OSU	Oregon State University
P	rainfall depth
P_a	atmospheric pressure
PCA	Plant Canopy Analyzer
PET	potential evapotranspiration

P_n	net rainfall
q	rainfall interception storage coefficient
Q	daily streamflow
Q_b	base or groundwater flow
q_H	specific humidity
Q_I	subsurface or interflow
Q_s	surface runoff depth
R	seep rate from soil moisture excess to each groundwater reservoir.
r_a	aerodynamic resistance
r_c	resistance to water vapours
RED	red reflectance
RMS	mean square error
R_{ns}	net radiation above canopy
R_s	incoming shortwave radiation
RSO	Rectified Skew Orthomorphic
RVI	ratio vegetation index
SC	coefficient in contributing area-soil moisture index relation
SS	subsurface reservoir inflow
SVP	saturation vapour pressure
T	mean daily air temperature
T_H	high temperature limit
T_L	low temperature limit
TM	adjusted daily maximum air temperature
TMN	daily minimum air temperature
TMX	daily maximum air temperature
TNLR	lapse rate for minimum daily air temperature for month 1 - 12
TXCR	maximum air temperature correction factor
TXLR	lapse rate for maximum daily air temperature for month 1 - 12
UNEP	United Nations Environment Programme
UPM	Universiti Putra Malaysia
VI	vegetation index
VI_g	vegetation index corresponding to that of the bare soil
VI_∞	asymptotic value of VI infinity
VPEND	ending day of vegetation period
YD	year day

ABSTRACT

Abstract of dissertation presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirements for the degree of Doctor of Philosophy.

A HYDROLOGIC MODEL FOR STUDYING THE CLIMATE CHANGE IMPACT ON EVAPOTRANSPIRATION AND WATER YIELD IN A HUMID TROPICAL WATERSHED

By

AMJAD NABI

January 1998

Chairman : Associate Professor Ir. Dr. Mohd Amin Mohd Soom

Faculty : Engineering

A procedure for estimating the impact of CO_2-induced climate and vegetation changes on actual evapotranspiration (ET), soil moisture and water yield in a humid-tropical vegetated watershed was proposed and evaluated. A distributed parameter modelling approach was used whereby a watershed was subdivided into relatively homogeneous ground response units (GRUs) to provide distributed parameter capabilities. A distributed parameter ET submodel was developed based on a biophysical approach for simulating actual evapotranspiration from a watershed with closed canopy cover of natural and planted vegetation. The hydrologic model, called humid tropical vegetation climate hydrologic model (HTVCHM), was developed by incorporating this ET submodel.

Leaf area index (LAI) was used in the model as a measure of vegetation structure and to quantify energy and mass exchange of canopies. The potentials of Landsat TM image was studied for LAI estimation using vegetation-index (VI) of rainforest, rubber and oil palm plantation. Canopy conductance (reciprocal of resistance) was also an important vegetative parameter which was included to represent CO_2-induced changes in vegetation. A procedure was presented and evaluated for subdividing a watershed into GRUs through the application of an unsupervised pattern recognition algorithm in conjunction with topographic data to Landsat Thematic Mapper (TM) data in a GIS environment.

To conduct the sensitivity analyses, climate and vegetation change scenarios were proposed based on the GCM prediction for this region and information from the literature. The procedure developed in this research is an effective and practical integrated approach to modelling the effects of climate and vegetation changes on the hydrologic response of watershed in this region. This procedure was applied and evaluated on the Trolak watershed of the Bernam River basin with a wet humid tropical climate and located in the south-east of Perak State of West Malaysia.

The model can simulate actual ET in humid tropical watersheds with closed canopy cover under both existing conditions and those assumed for CO_2-induced climatic and plant physiologic changes, such as LAI, and stomatal conductance. It also represents the spatial variations of the input variables and watershed parameters and provides a good framework for an integrated approach to modelling the effects of climate changes on water yield. The use of Landsat TM data to estimate the LAI illustrates the potential value of remotely sensed data for studying the humid tropical vegetation canopies characteristics. The VI-based LAI estimation method has proven to be simple to use and effective. The procedure developed for subdividing a watershed into GRUs provided reasonable results. The procedure was quick, easy to apply, and relatively less data demanding than the traditional ground-based approach.

The sensitivity analyses indicate a decrease in annual runoff by warming. Projected changes in monthly flows are identical to corresponding changes in annual flows. The climate change impacts are almost the same for wet and dry months. Warming have no effect on the timing and seasonality of runoff. There was no significant change in temporal runoff pattern with increased temperature alone or in combination with other scenarios. A significant increase in magnitude of annual water yield was found with increased rainfall scenario. Increases in temperature of 3° to 4°C decrease annual runoff of up to 12 to 16%. An increase in rainfall of 10% increases annual water yield by 18%. Annual changes in actual ET were found to vary by about -9 to +24% for the assumed scenarios. ET was found to be more sensitive to canopy conductance than to LAI. The changes in ET produced by warming in wet and dry months are almost the same and have equal effect on annual runoff. The greater sensitivity of annual runoff to rainfall than to temperature was found.

ABSTRAK

Abstrak disertasi yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah.

MODEL HIDROLOGI UNTUK MENGKAJI KESAN PERUBAHAN IKLIM KE ATAS SEJATPEMELUHAN DAN HASIL AIR DALAM KAWASAN TADAHAN TROPIKA LEMBAB

Oleh

AMJAD NABI

Januari 1998

Pengerusi : Prof. Madya Ir. Dr. Mohd Amin Mohd Soom

Fakulti : Kejuruteraan

Satu prosidur telah dicadangkan dan penilaian telah dibuat untuk menganggar kesan perubahan tumbuhan dan iklim disebabkan CO_2 ke atas sejatpemeluhan (ET) sebenar, lembapan tanah dan hasil air di kawasan tadahan tropika lembab. Satu pendekatan pemodelan parameter teragih telah digunakan di mana tadahan dibahagi kepada unit-unit respon bumi (GRU) yang lebih kurang sama untuk memberi kebolehan parameter teragih. Satu submodel ET telah dibina berdasarkan pendekatan biofizikal untuk simulasi ET sebenar daripada tadahan dengan tutupan sengkuap rapat dan tanaman. Satu model hidrologi yang dinamakan model hidrologi tumbuhan iklim tropika lembab (HTVCHM) telah dibina dengan menggabungkan submodel ET tersebut.

Indeks luas daun (LAI) telah digunakan dalam model sebagai ukuran struktur tumbuhan dan untuk mengira pertukaran tenaga dan jisim sengkuap. Potensi gambar satelit Landsat TM telah dikaji untuk menanggar LAI menggunakan indeks-tumbuhan (VI) kawasan hutan, getah dan kelapa sawit. Pengaliran sengkuap (salingan rintangan) adalah juga parameter penting yang diambil kira untuk mewakili perubahan tumbuhan disebabkan CO_2. Satu prosidur telah dibentangkan dan dinilai untuk membahagi tadahan kepada GRU melalui penggunaan algorithm pengenalan corak tanpa selia untuk data topografi ke data Landsat TM dalam persekitaran GIS.

Untuk menjalankan analisis kepekaan, sinario perubahan tumbuhan dan iklim telah dicadangkan berdasarkan ramalan GCM untuk rantau ini dan maklumat dari bahan penulisan. Prosidur yang telah dibina dalam penyelidikan ini adalah pendekatan bersepadu yang berkesan dan praktik untuk pemodelan kesan perubahan tumbuhan dan iklim ke atas respon hidrologi tadahan di rantau ini. Prosidur ini telah diuji di kawasan tadahan Trolak dalam lembangan Sungai Bernam yang terletak di tenggara Negeri Perak, Malaysia Barat.

Model ini mampu membuat simulasi ET sebenar dalam tadahan tropika lembab dengan sengkuap rapat dengan keadaan kini dan keadaan aggapan perubahan iklim dan perubahan fisiologi tanaman disebabkan CO_2, seperti LAI, dan pengaliran stomata. Ini juga merupakan variasi ruang pembolehubah input dan parameter tadahan, dan memberi kerangka yang baik untuk pendekatan bersepadu pemodelan kesan perubahan iklim ke atas hasil air. Penggunaan data TM untuk menganggar LAI menunjukkan potensi data penderiaan jauh untuk mengkaji ciri sengkuap tumbuhan tropika lembab. Kaedah menganggar LAI berasaskan VI terbukti mudah digunakan dan berkesan. Prosidur ini adalah cepat, mudah diguna dan kurang memerlukan data berbanding pendekatan biasa berasaskan data bumi.

Analisis kepekaan menunjukkan penguranan air larian dengan pemanasan. Unjuran perubahan dalam aliran bulanan adalah sama dengan perubahan aliran tahunan. Kesan perubahan iklim adalah hampir sama untuk bulan basah dan bulan kering. Pemanasan tidak memberi kesan ke atas ketika dan kemusiman air larian. Tiada perubahan bererti dalam corak air larian temporal dengan peningkatan suhu sahaja atau melalui gabungan dengan sinario lain. Peningkatan bererti hasil air tahunan diperolehi dengan sinario peningkatan hujan. Peningkatan 3°C hingga 4°C mengurangkan air larian tahunan sehingga 12 ke 16%. Peningkatan hujan sebanyak 10% menyebabkan peningkatan hasil air tahunan sebanyak 18%. Perubahan tahunan ET sebenar didapati berubah dari -9 ke +24% untuk sinario yang dikaji. ET telah didapati lebih peka kepada pengaliran sengkuap berbanding kepada LAI. Perubahan dalam ET akibat pemanasan di bulan-bulan basah dan kering adalah hampir sama dan memberi kesan yang sama ke atas air larian tahunan. Kepekaan air larian adalah lebih kepada hujan berbanding dengan kepada suhu.

CHAPTER I

INTRODUCTION

Background

A growing body of scientific opinion predicts that within the next few decades, the first global climate change resulting from increasing atmospheric concentration of carbon dioxide and other trace gases are likely to appear. Such a change in climate would be expected to have an effect on water resources. In humid tropics, the overall control of hydrological processes by global atmospheric and ocean circulation is more direct than in other regions because of the unique role of the equator (Klemeš, 1993). Recent studies suggest a regional warming trend over the humid tropics, with associated changes in certain critical hydrologic variables especially temperature and precipitation. It is also anticipated that important vegetation properties such as stomatal conductance, leaf area index, and water use efficiency will undergo major changes because of both changes in climate and enhanced levels of carbon dioxide. Current hydrological models in climate change studies have included temperature and precipitation but not the land use (vegetation) changes. Therefore, there is a strong incentive to develop hydrological models which are able to simulate the effects of predicted climate change on water resources. Development of modelling procedures to include the effect of both of these changes is the aim of this study. There are a number of issues, widely discussed in the technical literature, which must be taken into consideration in satisfying the objectives of this study.

One important issue is the extent to which atmospheric general circulation models (GCMs) should be coupled to hydrologic models. Global circulation models (GCMs) predict changes in temperature and in the amounts and distribution of precipitation as a result of this change. GCMs can provide the fundamental precipitation and temperature inputs required by hydrologic process models. Unfortunately, state-of-the-art GCM only provide estimates of climate features on a very large scale in the order of hundreds to thousands of kilometres and up. Even state-of-the-art GCMs use parameterization of surface hydrologic processes that are greatly simplified compared to actual hydrologic processes (Gleick. 1986; Nash and Gleick, 1991). The parameter averaging or "lumping", over large geographical regions, combined with oversimplification make the direct use of hydrologic variables generated by the GCMs an unsure recommendation at the watershed scale. In the humid tropics, this problem is exacerbated by the fact that most hydrologic models operationally available have been developed for temperate conditions and their structure does not make them readily transferable.

Another major issue is the question of "lumped parameter" versus "distributed parameter" models of the hydrologic processes themselves. There is little disagreement that spatial variabilities must be brought into the modelling process to more accurately reflect heterogeneities in soils, vegetation, and topography, even on a watershed scale. To bring spatial and temporal variability into the modelling process is the main concern of this study. Advances in remote sensing and a geographic information system (GIS) can be used to subdivide a watershed into similar hydrological areas and to obtain model parameters. The distributed parameter hydrologic model that is presented herein uses a new approach to subdivide a watershed into ground response units (GRUs) using Landsat Thematic Mapper (TM) data in a GIS environment.

One basic issue is whether existing hydrologic watershed models are appropriate for simulating climate change impact particularly in humid tropic regions. Existing models do not consider the effects of changes in Land use (vegetation) under a CO_2-altered climate on water resources. A suitable linkage should be developed for modelling interactions of land use changes, with evapotranspiration, soil moisture, and runoff.

Finally, there is a general agreement in the literature that the hydrologic implications of climate change cannot be realistically assessed without taking into account CO_2-induced change in vegetation. Changes in vegetation which include changes in the stomatal conductance, increased biomass, and higher level of water use efficiency due to enhanced level of CO_2 in the atmosphere, are expected (IPCC, 1990). These changes in vegetation have not been included explicitly in watershed hydrologic models. Recent work on ecological issues have identified leaf area index (LAI) as the most important single variable for measuring vegetation structure over large area, and relating it to energy and mass exchange for hydrologic and ecologic modelling (Running and Coughlan, 1988). LAI of natural vegetation is reported to have been successfully estimated from satellite resolution sensors (Asrar et al., 1984, Running et al., 1986, Curran et al, 1992). The procedure developed in this study incorporates LAI and stomatal conductance to adequately reflect the effects of vegetation on evapotranspiration (ET) and runoff.

The new procedure developed in this study is evaluated on Trolak watershed in Bernam River drainage basin. The Bernam basin is located in the south-east of Perak State, and north-east of the State of Selangor, Peninsular Malaysia. The basin has wet humid tropical climate. The water resources of the Bernam basin are extensively developed especially for irrigation of 20,000 ha paddy fields along the west coast. Even a marginal change in water yield due to projected change in climate may lead to widening the gap between water supply and water demand. In the past, no study has been done in this basin to assess water yield under projected climate change.

Objectives

In view of the issues and problems discussed above, the main objective of the proposed study is to develop, test, and apply a new procedure to better understand and model climate-landuse-evapotranspiration and hydrology in a humid tropical watershed using distributed modelling approach. Included in this main objective are the following specific objectives:

1. To develop an evapotranspiration (ET) model for vegetated watershed with appropriate representation of vegetation using a distributed parameter modelling approach.

2. To develop a distributed parameter hydrologic model by incorporating the above ET model for evaluating possible hydrologic impacts of climate change.
3. To develop and demonstrate a procedure for watershed subdivision into ground response units (GRUs) through the utilization of topographic data and the application of an unsupervised pattern recognition algorithm to Landsat Thematic Mapper (TM) data in a GIS environment.
4. To simulate the effects of changes in climate and land use variables over their credible range of scenarios under projected warming and double CO_2, on the actual evapotranspiration, soil moisture, and water yield so as to analyze their sensitivity to future climate changes.

An Overview

An overview of the tasks involved in accomplishing the overall objective of this study and summary of contents is given in this section. These tasks are described in detail in subsequent chapters, but are listed here as follows:

1. Review of relevant literature.
2. Conceptualize and develop a distributed parameter watershed ET model with explicit representation of vegetation.
3. Conceptualize and develop a distributed parameter hydrologic model to simulate the effects of climate and vegetation changes on water yield.
4. Conceptualize and develop a procedure for subdivision of watershed into GRUs using TM data applied to an unsupervised clustering algorithm in conjunction with topographic data.